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CCS for trade-exposed sectors: an evaluation of incentive policies

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Abstract

Several of the world's most carbon-intensive industries have no current alternatives to CCS for deep emissions reduction because much of the CO_2 is unavoidably generated by their production processes, not only from fuel use. As a consequence, many models of global decarbonisation foresee a potentially critical role for CCS.

The importance of CCS in industrial applications is not matched by existing policy attention and in some key sectors technological progress is slow. CCS suffers from several market failures that confront other low-carbon technologies. In contrast to the power sector, the trade-exposure of the manufacturing and hydrocarbon sectors that would need to deploy CCS exacerbates these market failures and poses significant challenges for policy that creates the foundations for long-term climate change mitigation.

Smart policy design will be able to facilitate a transition to a situation in which CCS is actually used to decrease costs, specifically those associated with greenhouse gas abatement. In a world that seriously confronts the climate challenge the first firms that install CCS will reap the benefits of reducing their marginal production costs and in the long run consumers will benefit from lower prices. In addition, producers and users of fossil fuels in sectors where marginal abatement costs could be very high, such as transport, will benefit from some relief from emissions costs as CCS in industrial applications creates headroom within a declining carbon budget.

This paper attempts to address two specific questions that policy makers will need to tackle in order to design such policies: how could technology development be accelerated to ensure its availability for deployment in the 2020s?; how might incentive policies be designed to support commercial CCS investments in trade-exposed sectors?

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1. Introduction

There has been a notable lack of progress in both technology and policy terms for CCS in most industrial applications, even compared to CCS in the electricity sector. One important difference compared to the power sector is that the products of the industrial sectors for which CCS is seen as a cost-effective mitigation option are commodities traded on international markets and their competitiveness is highly sensitive to production costs. CCS increases production costs, and the sectors have varying capabilities to pass on that cost to consumers.[†] Relocations of industrial production between countries due to changes in relative production costs are not immaterial to governments; they can threaten governments stewardship of their economies and affect employment.

Enabling trade-exposed sectors to take vital climate change mitigation actions, such as CCS, while retaining a competitive position, is a key challenge for CCS policy in a world with fragmented climate policies.

1.1. Why CCS in industrial applications is considered critical

At a combined emissions level of over seven gigatonnes of CO_2 ($GtCO_2$) in 2011, seven large industrial sectors including cement, iron and steel, chemicals and refining accounted for one-fifth of the total of 31 $GtCO_2$[‡] emitted globally. Emissions from each of these sectors are expected to grow by around 35% up to 2050 under current policies [1]. This is primarily because of increasing demand for consumer products and infrastructure and the importance of commodities such as steel, cement, liquid fuels and chemicals for the growth of modern economies. Materials like steel, carbon fibres and concrete are also fundamental to the supply chains of other low-carbon technologies – *e.g.* wind and nuclear power – that seek sustainable lifecycle performance.

However, efficiency measures and non-fossil energy options only have the potential to reduce the specific emissions from the above sectors' production by around 30%. As a consequence, without CCS or an equivalent breakthrough in materials and fuels production, the total emissions from these sectors will increase if economic growth continues at expected rates rather than diminish. In many industrial sectors there are no alternative technologies or methods on the horizon in the near- to medium-term to significantly reduce CO_2 emissions. CCS can help break the link between economic growth and the demand for industrial output, on one hand, and increasing CO_2 emissions, on the other hand.

1.2. Understanding the heterogeneity of industrial sectors and sites

The costs of applying CCS will vary between industrial sectors. These sectors produce different quantities and purities of CO_2, and the impact of using CCS would have different impacts on their production costs. As a result, sectors are at different stages of CCS development. Some sectors have already commercialised CO_2 capture technologies, due to the fact that there is an annual market for over 150 million tonnes of CO_2 ($MtCO_2$) for use in beverages, chemical manufacturing and enhanced oil recovery (EOR) [2].

In gas processing, where CO_2 is an impurity in extracted natural gas, and hydrogen production (for refining and chemicals manufacture), where CO_2 is a by-product, CO_2 is inherently produced as part of normal operation, little additional expense is required to purify and compress it for sale. While technology improvements are foreseen, costs are expected to remain between USD 10 and USD 40 per tonne of CO_2 avoided for CO_2 capture at gas processing and hydrogen production facilities [3]. Costs of CO_2 capture in several sectors – such as cement and iron and steel – remain uncertain due to a lack of experience and are estimated to be higher.

A range of sector- and site-specific factors will drive costs at individual sites, including: CO_2 concentration; CO_2 partial pressure; CO_2 volumes; ease of industrial integration; and location [4]. Compared with a single power plant, a 90% capture rate may not be realistic at each industrial site that applies CCS. Studies of steel production have

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[†] While electricity can also be traded internationally where interconnectors exist, it is more often the case that electricity is traded within national borders.

[‡] This total does not take into account emissions from land use, land use change and forestry.

found that a practical level of emissions avoidance via CCS for an integrated steelworks may be up to 60% for cost and energy penalty reasons [5]. Another example is a refinery site with multiple CO_2 sources, some of which have low capture costs, for example hydrogen production, but the cost of CO_2 capture from the remaining 80% of onsite emissions is likely to be much higher [6].

1.3. Progress to date

All large-scale CCS and CO_2 capture projects in operation by the first half of 2014 are in fact in industrial sectors. Altogether, 32 of the 65 large-scale integrated CO_2 capture projects that are listed by the Global CCS Institute as being either in planning or operation worldwide are on industrial processes [7]. Sectors that have a clear head start in terms of technical maturity have developed the technologies to take advantage of commercial demand for cheap CO_2 and their relatively low specific costs of CO_2 capture. In contrast, the smaller sizes of current CO_2 capture installations in some other industrial sectors, including cement and steel in particular, shows that they are significantly lagging behind.

1.4. Why the need for progress is considered urgent

For large-scale deployment in the 2020s, it is particularly important that the different CCS technology options are tested at progressively larger scales [8]. CO_2 capture technologies will move from pilot scale (less than 0.4 $MtCO_2$/yr) to demonstration scale (1 $MtCO_2$/yr and above) before deployment; each of these phases needs to operate for several years to generate the necessary knowledge and cost reductions. If serious emissions cuts are to be made by the middle of this century, rapid technical progress is a pressing need. Uncertainty related to costs needs to be reduced through additional studies, pilot projects and, most importantly, demonstration projects.

Just one or two pilot projects to date in each of the sectors with higher cost CO_2 sources is an insufficient level of experience, scale and diversity for investment in CO_2 capture at commercial scales. Sector-specific knowledge of the characteristics of the individual flue gas streams in different sectors is vital, in addition to any crossover learning between sectors. Uncertain costs are a hindrance to strategy and policy. Subsequent large-scale commercial deployment of the technology could take several decades, due to the long-lived nature of manufacturing infrastructure and slow turnover of stock. Many cement plants and integrated steelworks operating today were established many decades ago – some are 50 years old or more – and usually only undergo major refurbishments in line with the lifetimes of key pieces of equipment, often around twenty years.

This paper focuses on the policy approaches that might be appropriate to overcome the challenges to deploy CCS in industry.

2. Key policy challenges for CCS in industrial applications

CCS, like other low carbon technologies that are pre-commercial, faces market failures [9]. Five market failures that can justify policy intervention have been found to be relevant for the development and deployment of CCS (Table 1) [10]. The first two of these are the most significant and interact in a vicious cycle whereby the absence of a market driver for investment in projects leads to a lack of knowledge of real-world CCS costs and operation, which impedes effective policymaking and raises the risk of investment. These two are considered briefly below.

2.1. Negative externality: the difficulty of internalising CO_2 costs

Adding the costs of CCS on to the production costs of traded commodities is equivalent to (or greater than) internalisation of the costs of CO_2 emissions. Climate policies today, including carbon pricing systems, are regional, yet trade is often global. If trade across borders is open, cost increases could undermine competitiveness of these sectors in regions that pursue independent policies to internalise the social and environmental costs of CO_2 emissions. In comparison with the electricity sector, which is more nationally or regionally organised and where costs of more expensive technology can more easily be passed on to customers, regional climate policy in trade exposed sectors can have a more distorting effect. If a firm's main competitors are outside the regime, then their competitors will face no equivalent increases in costs.

Table 1. Market failures leading to the undersupply of CCS technology and deployment

Market failure	Policy objective
Negative externality	Markets do not take into account the economic, social and environmental costs of CO_2 emissions.
Public good	Knowledge about comparative efficacies and costs of different technologies can be considered to be a public good.
Capital market failures	Information asymmetry and imperfect information can result in under-provision of capital. For example, information about CO_2 capture costs and performance for early projects may be unequally distributed between different parts of the value chain. Capital providers may be unwilling to provide finance if they are unable to assess risk dependably.
Imperfect competition	Undesirable market power leading to high prices can be exerted by firms that hold monopolistic or oligopolistic positions. This is a particular issue for technologies that reply on networks to operate most efficiently.
Complementary markets	If different parts of the vertical value chain are under different ownership, investments in CO_2 capture, transport or storage depend upon unpredictable and sub-optimal decisions made by the other two elements.

Facilities whose output competes for market share with production from other countries may only be able to pass on some, or even none, of the increases in production costs associated with CO_2 abatement. This can undermine the economic rationale for CCS, which can involve a significant increase in production costs. In the EU ETS a 30% increase of production costs is considered to be the maximum that a firm could tolerate without severely threatening international competitiveness [11]. This means that under an incrementally rising regional carbon price, firms could become uncompetitive before the carbon price reached the level at which CCS would become viable. The consequence can initially be a reduction in capacity utilisation in regulated regions and an increase in non-regulated regions. It can also encourage location of new capital investments in non-regulated regions. The competitiveness of the sector within that country can fall and "carbon leakage" may result in some circumstances; both outcomes are generally considered to be undesirable.

Looking at the impact of CCS on a sector's competitiveness, two factors are critical, and they vary between sectors: exposure of a sector in a given country to international trade; and the relative impact that CCS would have on production cost. If a sector was an "ideal" candidate for the uptake of CCS, it would have both a low exposure to global competition *and* a low impact on the cost of the final product. However, partly because products traded over large distances are more likely to be of higher value and margin, no sectors have the ideal combination of low trade exposure and low relative cost increases [12].

2.2. Knowledge as public good: lack of first-mover advantage

Another challenge (market failure) facing CCS is the lack of a clear first-mover advantage. Developing CCS at pilot or demonstration scale can be a costly undertaking. If the technology is unlikely to be deployed within a timeframe in which the knowledge can be competitively appropriated, the costs are likely to outweigh the knowledge generated. The ability of a single firm to reap the rewards of technology investment are further reduced if technology projects are costly and individual firms are less able to contribute to an overall solution, increasing the risks of so-called free riders. In trade-exposed sectors the threats to competitiveness can be greater if competitor firms, which are not covered by equivalent climate policies, do not make equally large investments in technology development.

First movers can also face a regulatory dilemma. While the development of technological solutions can be an insurance investment against future regulation and can have reputational benefits for a firm, the commercial-scale demonstration of the technology can increase the likelihood that its use will be compelled by regulatory measures. This dilemma can constrain the extent to which firms are willing to invest in the early stages of technology demonstration.

2.3. A challenging climate for addressing market failures

The long-term challenge of internalising CO_2 costs through CCS has been compounded by economic and political realities that have hindered investment in CCS technology projects in the near-term. The *economic and financial crisis* explains some of the lack of progress with CCS in some sectors. Investment in new technologies suffers if investment in capacity in general is stifled by falling demand. In order to develop new technology such as CCS, prospective operators need confidence that their industrial base will be maintained over the coming decades. While expansion of energy-intensive sectors continued in some regions, the regions from which leadership on low carbon technologies was expected have suffered most from the financial crisis. Another manifestation of the crisis has been the reduction of available public funds for CCS development.

Changing patterns of capital stock have resulted from demand and competitiveness factors related to the crisis but also from other factors, such as the costs of energy, land and labour and the availability of skills. Since 2008, industrial capacity additions have often been greatest where the costs of all factors of production are lower and where the rates of demand growth are higher. This includes, for example, China and South East Asia. Despite a growth in R&D activity in these regions, the geographical disconnect between regions were CCS R&D is primarily undertaken and where capital stock is added has grown.

Another result of the crisis and the changing patterns of capital stock is the current overcapacity in some sectors. For example, in the European steel sector, low margins mean that profits can in some cases be absorbed by maintenance of existing assets, leaving little available capital for long-term technology development, especially in a region where consolidation is more likely than capacity additions. Although, in theory, multinational firms under carbon pricing schemes such as the EU ETS could receive windfall profits from the combination of free allowances and output reductions [13], these revenues are as likely to be reallocated to regions where returns on investment are greater as they are to be invested in low-carbon technology. Between 2006 and 2012, China added 440 million tonnes of steel capacity, more than double the total European capacity [14]. However, today it has 200 million tonnes of unused capacity and its steel mills operate today below the worldwide average capacity utilisation [15].

3. Stepwise policy for CCS in industrial applications

Deploying CCS for climate change mitigation purposes requires policy action. Effective support for CCS calls for a combination of policy tools within a coherent policy architecture, where each policy addresses a separate challenge or market failure. To combine flexibility and certainty, a “gateway” approach that sets policy within a stable framework, so that the broad architecture and rules of policy evolution are certain, has been proposed [16]. This approach has clearly defined break points that denote changes in policy designed for three difference phases.

- **Phase 1**. The aim is to generate the public good of knowledge of different CCS technologies. This phase would help identify successful technologies, potential cost reductions and minimise information asymmetries. Early projects may not immediately be commercially useful to those undertaking the investment but would be vital to secure the option of future timely CCS deployment, which would provide returns to public and private sectors.
- **Phase 2**. While sectoral CCS costs remain higher than economy-wide marginal abatement costs, the key aim will be to facilitate investment in CCS projects while reducing public spending and risk exposure. In the absence of proven cross-sectoral climate policies, the key aim is to address capital market failures and unlock private investment in CCS projects for continued learning-by-doing.
- **Phase 3**. In the longer-term, the most efficient option is likely to involve addressing the market failure of externalised CO_2 costs through cross-sectoral, technology neutral penalties, such as carbon pricing. Public subsidies would be reduced and costs borne by the private sector.

3.1. Phase 1: Technology demonstration to secure the option of CCS

The policy goal at this point is not to make emissions reductions *per se*, but rather to advance CCS technology, understand potential cost reductions through learning-by-doing and establish commercial arrangements between the different stages of the value chain. This means that such policies will continue to be relevant to some technologies and sectors even after others have moved to the next policy phase. For example, capture technology for cement manufacture is currently at the pilot project stage, while that for gas processing and hydrogen production can in many cases already be considered commercial, especially if paired with EOR.

Success is measured in terms of knowledge and cumulative experience provided, rather than in terms of emission abatement achieved. Suitable public support instruments for CCS technology development include direct financing, such as grants, co-investment equity, debt, credit guarantees and insurance products. If direct capital funding needs to be secured to mitigate the risk of insufficient investment in a public good, there are different instruments to achieve this. These instruments can share the costs and risks with the private sector in different ways [17].

Projects at this stage of development are not profitable in the short term but will provide a public good and a (unknown but non zero) reward to first-movers from the private sector. Private sources of financing are likely to be unavailable or expensive. The full costs of such projects may need to be shared between the public and private parties that will benefit (Table 2). The challenge for policy is to capitalise on the willingness of beneficiaries to provide funds in accordance with their priorities, risk and ability to commit. Public funding generates leverage for governments to disseminate information generated from projects. This has been accounted for in many public funding agreements for CCS projects [18, 19].

Table 2. Beneficiaries of Phase 1 CCS projects in industrial applications

Beneficiary	**Direct/ indirect benefit**	**Explanation**
Industrial producers	Direct	The development of CCS technology would enable them to meet their emissions obligations at lower cost.
Governments with a stake in the sectors	Direct	Energy-intensive industries and raw material exports are potentially highly valuable to many countries future prosperity for geographical, structural and balance-of-trade reasons. These governments may benefit most from supporting sectors and technologies in which they see a comparative advantage.
CCS equipment and service providers	Direct	Those for whom CCS represents a new opportunity to sell goods and services to users of the technologies.
Fossil fuel producers	Direct and indirect	If the world has a limited amount of CO_2 that it can emit from fossil fuel use over the coming decades in order to stabilise the global climate then the only way it can use more fossil fuels than prescribed by this “carbon budget” is through the use of CCS. This includes fossil fuels used by CCS-equipped sectors and others, such as transport. The refining sector therefore indicates a potential intersection of incentives.
Fossil fuel users	Indirect	CCS in industrial applications could create headroom for other emissions that are less attractive to avoid. The provision of liquid transport fuels to the airline or passenger vehicles sectors, where CO_2 abatement may be very expensive, is an example.
Purchasers of ‘green’ CO_2	Direct	Those that could make use of the captured CO_2. Policy can create incentives for chemical or fuel producers to incorporate CO_2 as a raw material. The European Commission has proposed that renewable liquid and gaseous fuels of non-biological origin shall be considered to be four times the energy content of other biofuels [20]. Under the German Energy Act, however, only fuels made from CO_2 that is mainly from renewable sources could be eligible for subsidies [21].

3.1.1. International sectoral cooperation

Many of the benefits to the private sector are knowledge-based and relate to gaining an understanding of technology operation and commercial practices. Knowledge is a nonrival but excludable good, which is undersupplied by the market and first movers are wary of free riders. As new knowledge can benefit a community of beneficiaries and be shared at zero marginal cost, a CCS project may be considered a good investment for a sector if the costs were spread between all participants but a poor investment for a single firm with large upfront costs and uncertain returns.

Sectoral approaches to climate change policy have been proposed to overcome regional differences in policy [22]. Here we use the term to refer to collaboration on technology development that can benefit all willing actors in a given sector. It can help the international community target areas where technological breakthroughs are needed, capital investment is long-lived and where incentives to constrain emissions are inadequate [23, 24].

Collaboration can reduce the costs to each actor of insuring against future high carbon prices or strict climate regulation, despite reducing the ability of each firm to gain an advantage from the resulting knowledge. It may not be limited to collaboration within a sector; firms in different sectors are typically not in competition with one another and have an incentive to identify non-competitive technology areas. Cross-sectoral collaboration to test various flue gas capture options on different flue gases could be of interest in this respect, especially through open-access facilities.

Sectors could agree to targets and timetables for the development of CO_2 capture technologies and pool or coordinate effort in consortia to achieve them, especially in areas that are considered further from core competitive competences. Pledges under technology-oriented sectoral cooperation might be credited in terms of GHG reductions or linked to global benchmarking and diffusion of best practice under international agreements.

In the case of CCS, much of the value chain is outside the current operational competence of the steel and cement sectors. This is of particular importance in these sectors, for which the core production equipment is supplied by a small number of engineering firms rather than being the intellectual property of the operators themselves. Partners could undertake engineering and cost studies of CO_2 capture options and process integration, and jointly lead promising technologies through sequential stages from pilot to demonstration scale. The Ultra-Low CO_2 Steelmaking (ULCOS) and the European Cement Research Academy (ECRA), both in Europe, are two examples of industry-led initiatives on which technology-oriented sectoral cooperation could build.

Sectoral cooperation could also proceed as a means to generate funds for technology development. The Australian Coal Association voluntary contribution scheme is an example of a low level of burden spread across a large industrial output [25]. Schemes that hypothecate revenue from emissions trading to fund CCS projects, for example, implicitly recognize the need to spread costs across as many beneficiaries as possible. Another example, which has been suggested by the European Commission, is to require suppliers of fossil fuels to buy CCS certificates equivalent to a proportion of their embedded emissions [26]. The funds from the certificates could be used to fund CCS projects that would benefit the purchasers of the certificates in the longer term.

3.2. Phase 2: Ensuring investment for early deployment

Phase 2 in the proposed gateway approach employs policy instruments that enable a wider supported roll-out of the technology in commercial markets. The priority is to address the lack of capital available to projects that can further move the technology along the learning curve. CO_2 costs cannot be fully internalised by the private sector, primarily due to trade exposure concerns. As with many existing support schemes for renewable energy, cleaner production is rewarded and the competitiveness risks associated with the CO_2 cost externality are reduced. Early deployment is a transitional period between Phase 1 and Phase 2.

A desirable policy package for trade-exposed sectors will differentiate between sectors according to technological maturity and competitiveness concerns. It will also transfer risk and responsibility to the private sector as the phase proceeds. We have formulated five principles of such a policy package in Table 3.

Table 4 provides estimations of the compatibility of these principles with a number of selected policy measures, indicating that combinations of instruments are necessary to guide trade-exposed sectors through Phase 2. While various instruments could have particular merits in certain regions or contexts, CO_2 purchase commitments seem particularly interesting due to their potential to address the greatest number of principles simultaneously.

Table 3. Five principles to guide policy making for Phase 2

Principle	Description of measure that would fit this principle
Cross-sectoral	Does not discriminate against any sector and incentivises lower cost opportunities to gain learning about CO_2 capture, transport and storage. For example, CCS for hydrogen production for ammonia synthesis would precede CCS for steel production. Reduces administrative complexity
Continuous incentive to abate	Provides an incentive to abate an additional tonne of CO_2 at the margin. Unlike performance standards, which can set a threshold to abatement levels.
Shares investment risks with private sector	Addresses capital market failures but reduce the risk burden on the public sector as development progresses
Reduces operational risks	Minimises risks of stranded CCS assets in order to deliver continued learning and value-for-money. Incentives could be contingent on operating the CCS facility, such as those that target quantities of CO_2 captured and stored (e.g. portfolio standards) and those that are linked to prices (e.g. production subsidies and CO_2 pricing).
Long-term potential for market support	Could ultimately regulate CO_2 emissions in a technology neutral manner without imposing continuing costs or expert project assessments on government. Do not significantly interfere with other policy measures in ways that reduce motivation to innovate, lower economy-wide carbon prices or insulate sectors from competition.

Table 4. Potential incentive mechanisms that could be considered for early deployment

Incentive mechanism	Cross-sectoral	Continuous incentive to abate	Shares investment risks with private sector	Reduces operational risks (risks of stranded CCS assets)	Long-term potential for market support
Investment tax credit	Yes	Potentially	Yes	No	No
Public co-investment in projects	Yes	Potentially	Yes	No	No
Production/emissions subsidy	No	Yes	No	Potentially	No
Emissions performance standard	No	No	No	Yes	Yes
Portfolio standard	No	Up to a set limit	No	Yes	Yes
Feebate penalty and reward system	No	Yes	No	No	Yes
CO_2 purchase commitment	Yes	Up to a set limit	No	Potentially	No
Production tax credit	Yes	Yes	No	Yes	No
CO_2 tax/cap and trade	Yes	Yes/Potentially	No	Partly	Yes
Baseline and credit reward system	No	Yes	No	Partly	Yes

3.2.1. CO_2 purchase commitments as a potential support mechanism for early deployment

In this section, one incentive mechanism is selected for further discussion. It will not necessarily be appropriate in all cases and is unlikely to be sufficient in any sector or region by itself. Nevertheless is does offer a number of advantages compared to other options and these are explored further. The concept of CO_2 purchase commitments is as follows:

- A government would announce its intention to purchase a quantity of stored CO_2 each year. This could include commitment to purchase an increasing minimum amount of CO_2 in future years, providing some certainty regarding volume and duration.
- Firms whose CO_2 was stored rather than emitted would be issued with certificates verifying the amount of CO_2 stored in accordance with a regulatory regime that provides confidence that the CO_2 is geologically retained

- Firms would then be able to sell these certificates to a government agency, which would purchase at the lowest available price, for example in a reverse auction. Reverse auctions held in advance can reduce public risk but will raise the project investment risk and remove the marginal incentive for continued abatement.
- A market for the certificates could be allowed to develop if parties had different expectations about certificate price evolution and wished to hedge their risks.

In addition to meeting the principle of cross-sectoral neutrality, CO_2 purchase contract mechanisms could have little or no impact on competitiveness for trade-exposed sectors because additional costs of CCS would be covered. By targeting a fixed quantity of CO_2 stored, rather than subsidising output, producers' cost and market price uncertainties can be addressed. If the market can withstand it, however, a competitive market for certificates could encourage firms to accept higher shares of the cost and risk in order to make competitive bids. The competitiveness of reverse auctions is central to the efficiency of the instrument. Governments could pay above the socially efficient level for CO_2 abatement and carbon leakage avoidance if reverse auctions are not sufficiently competitive, including double counting under carbon pricing or other systems designed to reduce emissions and maintain competitiveness.

On the other hand, reducing the amount of competition in the market by implementing some bilateral multi-year contracts – even before investments in CO_2 capture facility are taken – could guarantee revenues for operation.[§] This would increase the number of potential participants in sectors where CCS is further from cost-effectiveness and where first-movers run the risk of being undercut in later auctions. As perfect technology neutrality would neglect sectors with higher capture costs and competitiveness risks, uneven technology learning and a lack of mature technologies passing to Phase 3 of support would result. CO_2 purchase commitments could be flexible enough to allow government to commit to purchasing a certain proportion of the certificates from a specific sector.

This flexibility gives CO_2 purchase commitments some options to target specific investment risks and technology priorities. Nevertheless, the funding that would allow governments to make upfront commitments, especially over extended periods, would still need to be secured. In some countries, the raising of revenue for such a system could be linked to the repeal of fossil fuel subsidies, which amounted to USD 523 billion in 2011 [27]. Some of the same instruments suggested for Phase 1 could be appropriate to spread the burden thinly across public and private beneficiaries alike, e.g. sectoral levies, certificates or hypothecation of CO_2 pricing revenues. Carefully structured capital or production tax credits could furthermore help facilitate access to capital and address competitiveness concerns to reduce risk premiums. Collaboration between countries could reduce the effective level of national trade-exposure and thus increase the opportunities to share the cost burden with operators.

3.2.2. Other possible policy tools

The competitiveness impacts of climate policy relate to trade exposure and the cost impact of mitigation measures such as CCS.

Some sectors are less trade-exposed and some cost-sharing between firms and government may be preferable. In the cement sector, for example, portfolio standards could be applied as the products are relatively homogenous. The portfolio standard could, in fact, complement a CO_2 purchase commitment by setting a proportion of production that would need to be covered by CCS, a declining percentage of which would be purchased by the government each year through reverse auctions. Note, however, that EUR 15 to EUR 20 has been proposed as an ETS price that could stimulate imports of cement to the EU [28].

Sectors that are trade-exposed but where the potential cost impact of CCS would be lower may also be incentivised through portfolio standards, such as the certificate scheme for the fossil fuel production sectors mentioned in Section 3.1.1. However, higher levels of trade exposure may mean that lower proportions of CO_2

[§] Longer contract lengths would limit a government's ability to profit from future cost savings and lower-cost market entrants. Thus, the contracted proportion of the CCS project's full capacity could be reduced over the lifetime of the project and the remainder would be subject to bidding in reverse auctions to increase public value for money. The volume and length of these contracts would need to be calibrated according to the risk that CCS capacity could become stranded if future projects benefit from cost reductions or cheaper CO_2, and the impact of this risk on the attractiveness of the investment proposition and the overall benefit of future cost reductions. Contract prices could be determined through a tender process linked to external factors such as fuel prices and carbon prices, minimising any premium paid for bilateral contracts.

production can be covered by certificates. Other possible mechanisms to address less trade-exposed sectors include emissions performance standards and feebates. An approach to emissions performance standards is to apply them on a lifecycle basis, as is the case with the European Fuel Quality Directive [29]. Emissions performance standards in the natural gas production sector could be set at a level that obliges producers of acid gas (with high CO_2 content) to store the separated CO_2 in order to be able to access the natural gas market. Experience in Norway and Australia suggests that such an approach, even at a national level, could avoid the venting of pure CO_2.

Designing the basis for both production subsidies and portfolio standards is inherently complex in sectors that have product differentiation (e.g. different steel qualities) or multiple product streams from single plants (e.g. refining).

A further approach to supporting early commercial projects could be to link emissions reductions from industrial processes with other policy mechanisms in less trade-exposed sectors. This type of approach would be similar in concept to offsets in some emissions trading sectors, i.e. it would allow firms with an emissions reduction incentive and a high marginal abatement cost to benefit from cheaper mitigation options in other sectors. A conceivable situation could be one in which electricity suppliers can benefit from financial support for the application of CCS to their power plant (or face an emissions performance standard) but can equally benefit from the same level of support if they invest in a CCS project of the same magnitude in a sector with lower CCS costs.

3.2.3. Reducing trade exposure instead of compensating for it

Higher levels of trade exposure potentially require governments to take on more of the costs and risks of CCS if the application of climate policy is not equal in all regions. An alternative to increasing the public burden is to take steps to reduce trade exposure. Figure 1 shows trade exposure levels for three sectors and selected countries that have current CCS activities. The trade exposure metric used is that which is employed for assessment of carbon leakage in the EU emission trading system.

Figure 2 shows the impact of recalculating the index for the hypothetical case in which trade with specific partners were not considered to be exports. The resulting percentages show by how much the index would be reduced by for each country and each partner. High percentages indicate that if policies in the two countries were aligned, they would not need to overcome high trade-related policies in the two countries were aligned, they would not need to overcome high trade-related barriers to implementation. Black cells indicate that the findings for the two countries are symmetric; for a country that would benefit most from coordination a given partner, the partner would also benefit most from coordination with that country. Canada and the US, France and Germany and Japan and Korea appear to be good candidate pairs for greater cooperation in CCS in industrial applications. To a large extent in EU countries, cooperation already exists.

3.3. Phase 3: Internalising CO_2 costs for wide deployment

The priority of this phase is to abate CO_2 emissions and fully internalise CO_2 costs within firms' decision-making, while accounting for any regional differences and carbon leakage risks. Wide deployment would proceed after Phase 2 if CCS is a cost-effective option in a given sector, ideally within a broader technology-neutral climate policy on a global level. Multi-sector or economy-wide carbon pricing, performance standards or combinations of these, such as a trading system with emissions benchmarking, would be possible instruments. In Norway, the introduction of a USD 55/tCO_2 carbon price for the oil and gas sector in the early 1990s triggered the implementation of CCS for gas processing, a technology that was relatively mature [30].

As a highly capital intensive technology, CCS investment risk varies strongly with carbon price volatility and long-run societal costs might be reduced by a carbon price floor. Abadie and Chamorro estimate that CO_2 trigger prices for CCS could rise by a factor of four for the case where carbon price volatility is 50% rather than 0% [31]. Some continued support may be justified even under a functional and inclusive CO_2 emissions system and may be vital under asymmetric carbon pricing in different regions.

It could be challenging for governments to justify continued support for CCS in the third phase if it is still a relatively expensive CO_2 abatement option. This is especially true for countries with cap and trade systems whereby public support for CCS would not reduce the overall emissions under the CO_2 emissions cap. But, as policies move from supporting technology learning to internalising the CO_2 externality, tools such as free allocation, BCAs or equivalent may be essential to account for regional policy differences.

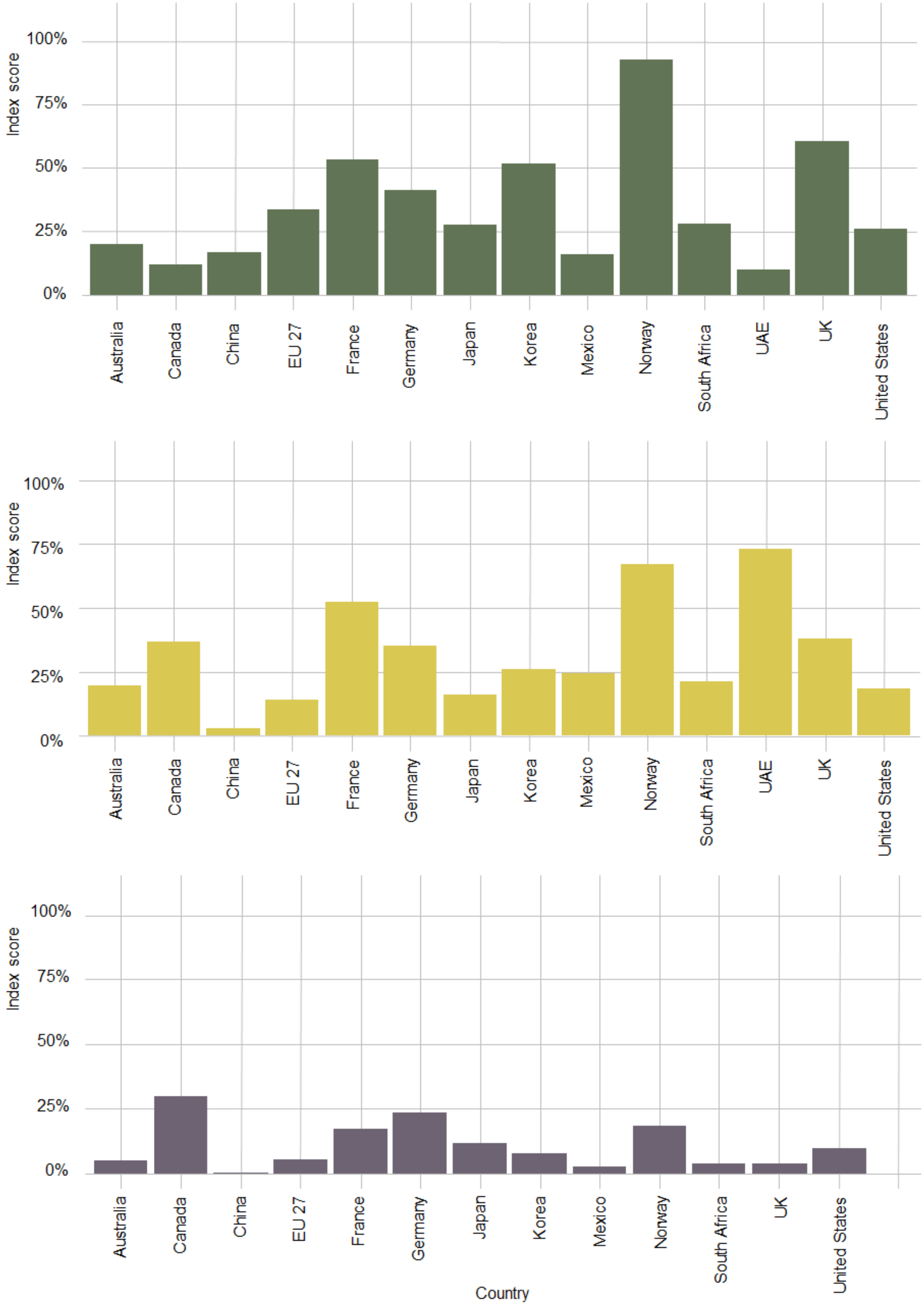

Fig. 1 Selected national trade exposure indices for the refining (top) iron and steel (middle) and cement (bottom) sectors

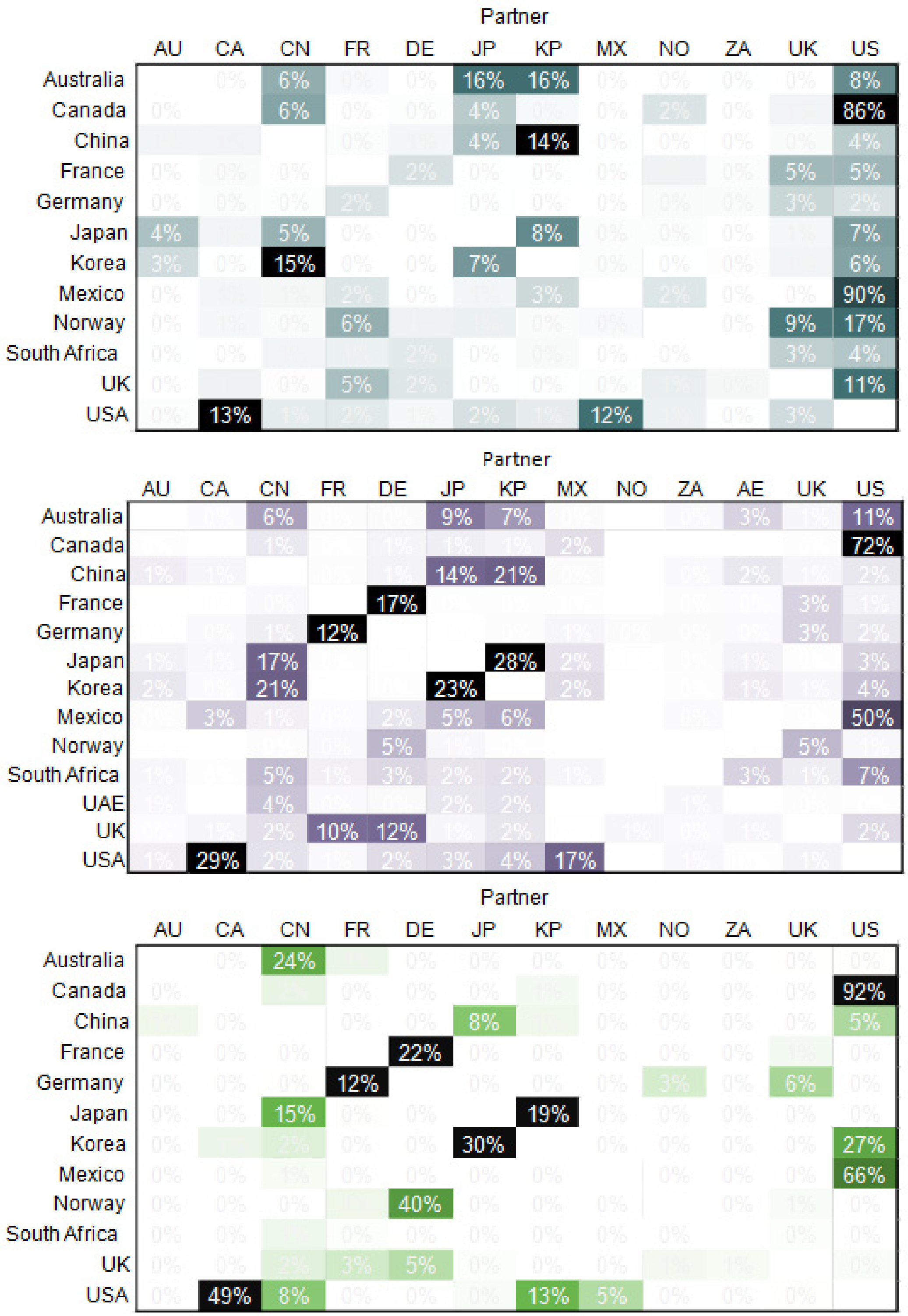

Fig. 2 Impact of policy cooperation on trade exposure in the refining (top) iron and steel (middle) and cement (bottom) sectors

3.3.1. Free allocation or tax exemptions

Free allocations or tax exemptions/rebates may be necessary for the duration of the period that a global carbon price is not in effect. To retain competitiveness and protect against carbon leakage while incentivising CCS, free allocations would need to be based on emissions intensity before the addition of CCS, and linked to output rather than installed capacity to avoid abatement through reduced capacity utilisation [32]. In addition, strong political commitments or "front loading" of a firms' allocation could encourage investments in assets with multi-decade lifetimes compared to the shorter timeframes on which free allocation or tax rebates are generally determined.

If the level of free allocation is sufficient to avoid carbon leakage, it provides no incentive by itself for the adoption of mitigation technologies or continued low carbon innovation. In theory a firm might apply CCS if its costs were lower than carbon prices and if its entitlement to the free allocation were not diminished by applying CCS. In practice, however, firms are likely to value the certainty of free allocation more highly than the uncertainty of carbon prices, especially if CCS costs are not considerably lower than carbon prices. More importantly, perhaps, firms are likely to perceive a significant risk that for budgetary reasons governments might remove their entitlement to free allocation after the installation of CCS and before the investment in CCS is paid off.

3.3.2. Border carbon adjustments (BCA)

BCA is alternative to free allocation or tax rebates for trade-exposed sectors that are sensitive to carbon prices [33]. BCA regimes could prevent carbon leakage and preserve regional competitiveness by levelling the playing field. It has been noted that the absence of a carbon price on imports could comprise an implicit subsidy to dirtier production in non-regulated markets [34].

To incentivise CCS, the protection afforded by a BCA would need to remain after CCS were installed and long-term binding commitment to this might be required to overcome investment risks. The BCA would need to distinguish between different types of product within a sector, e.g. different types of steel, to avoid unequal impacts on more CO_2-intense production processes within a sector. BCA schemes that cover only basic materials and not manufactured goods could disadvantage domestic manufactured goods yet applying BCAs to all manufactured goods would be highly complex and trade flows may re-route to minimise cost impacts [35]. Consequently, BCAs may be more easily applied in sectors such as cement (where products are more homogenous), compared to refining or steel production, all else being equal.

3.3.3. Inclusion of consumption within carbon pricing systems

Noting that output-based free allocation for the cement sector may provide some of the right signals for CCS but would not incentivise clinker substitution, consumer choices for composite cement or product substitutes, a complementary approach has been mooted [36]. Inclusion of consumption within carbon pricing systems could involve making firms liable for a charge on their consumption of products from energy-intensive sectors regardless of whether these products, such as clinker, were sourced domestically or imported. The intention would be to pass on a proxy for carbon cost to downstream users without imposing the cost on the primary producer. Downstream products freely traded nationally and internationally would bear the carbon price as they are for tobacco and liquor in the EU ETS today.

In comparison to BCA, this option may avoid free trade concerns. The practicalities remain to be explored, including how to ensure that competing products using raw materials from different sectors all face comparable carbon costs.

4. Delivering success: addressing the other market failures

If the undersupply of CCS knowledge, capital and the externalisation of CO_2 costs are overcome, successful deployment of CCS will still demand that other market failures are also addressed during the three phases.

4.1. Imperfect competition

Multi-year, bilateral CO_2 purchase contracts, incentives linked to previous production levels and public grants for projects that are not optimised for future network expansion can disadvantage later entrants into CCS. These aspects can be mitigated by reducing the lengths of contracts for CO_2 or allocating to the public the risk that future local sources of CO_2 do not emerge to fill pipelines that are designed with future network expansion in mind. Monopoly power in CO_2 transport networks has been dealt with in existing regulations; see [37, 38].

4.2. Complementary markets

It has been suggested that CO_2 capture development in industrial applications need only proceed once CO_2 transport and storage have been developed and commercialised by other sectors and third parties. Energy-intensive industries highlight the acute need for a commercial CO_2 transport and storage business to become available for the off-take of captured CO_2. Yet, the developers of transport and storage solutions, who typically are not in the same sectors, may equally insist that the opposite be true. Governments can be instrumental in reducing the first-mover risks on both sides.

It is unlikely that many heavy-emitting firms, with the possible exception of refiners and gas producers, will evolve to become integrated into the CO_2 storage business in the near to medium term. If CO_2 emitting firms prefer to contract with third parties for the capture, transport and storage of their CO_2, this will create complexity and potentially add costs associated with the transfer of liability. While this presents a coordination challenge for some sectors, the vertical integration of refining and gas processing into CO_2 transport and storage presents an opportunity. Vertical integration can overcome the additional costs associated with contracting in the value chain and skill shortages for early projects.

Ensuring that players in different sectors and different parts of the value chain are coordinated can also enable deployment at a local level. The evolution of clusters of CCS-equipped industrial facilities could be promoted by government to help sectors be “CCS ready” and plan to share a local CO_2 transport and storage infrastructure, which could be anchored by the presence of CCS on a major local emitter in the power sector. Planning for the stepwise deployment of CCS in major industrial clusters includes investigating accessible CO_2 storage sites, engaging all actors in CCS policy discussions and considering requirements that would make local sectors increasingly CCS ready.

5. Conclusions

The key difference between developing policy for CCS in industrial applications compared to the electricity sector is that it must take greater account of both trade-exposure and the lack of alternatives for low-carbon production in some sectors. These issues can exacerbate the impacts of market failures in comparison to the electricity sector. A further crucial difference is the range of different CO_2 capture costs and scales in different industry sectors and within sectors.

In a gateway approach, different policy instruments will be appropriate in the three different phases. The types of instruments used in the three phases must dovetail with one another to avoid breaks or unmanageable changes in support. The sources of funding in Phase 1 and Phase 2 might, for example, come from the same sources. As the available funds are likely to be constrained in the near term in most regions of the world, it is important that policy makers consider whether costs can be shared appropriately with the beneficiaries of CCS knowledge and experience.

The types of instruments that will be appropriate at different times will also vary by sector and technology. While some technologies are already mature and available to be deployed to assist with learning-by-doing for CO_2 storage, others are less mature for reasons of costa and trade exposure. Less mature (in terms of CCS) and more trade-exposed sectors are likely to be motivated to undertake CCS projects more by “carrots” than “sticks” in the near term. Policy makers would be encouraged to build carefully on willingness to develop CCS technologies and projects where it already exists. In sectors such as steel and cement in developed countries this willingness is often fragile.

We conclude that climate policy and industrial policy interact strongly in the area of CCS in industrial applications and governments urgently need to reconcile the two if they are to secure the necessary technology progress in a timely manner.

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7. References

[1] IEA. Technology Roadmap: Carbon Capture and Storage. Paris: OECD/IEA; 2013
[2] ADEME. Panorama des voies de valorization du CO_2. French Agency for Energy and Environment: Angers; 2010.
[3] IEA. Global Action to Advance Carbon Capture and Storage: A Focus on Industrial Applications, Annex to Tracking Clean Energy Progress 2013. Paris: OECD/IEA; 2013
[4] IEA. Policies to incentivise CCS in industrial applications. In CCS 2014: What lies in store for CCS? Paris: OECD/IEA; 2014
[5] IEA GHG. Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill). Report 2013/04.IEA GHG. Cheltenham: UK; 2013.
[6] Van Straelen, J., F. Geuzebroek, N. Goodchild, G. Protopapas and L. Mahony. CO_2 capture for refineries: a practical approach, *International Journal of Greenhouse Gas Control* 2010, 4:316-20.
[7] GCCSI. The Global Status of CCS: 2013. Canberra.: Global CCS Institute; 2013.
[8] IEA and UNIDO. Technology Roadmap: Carbon Capture and Storage in Industrial Applications. Paris: OECD/IEA; 2011.
[9] IEA. A Policy Strategy for Carbon Capture and Storage. Paris: IEA/OECD; 2012.
[10] Krahé, M., W. Heidug, J. Ward and R. Smale. From demonstration to deployment: An economic analysis of support policies for carbon capture and storage. *Energy Policy* 2013, 60:753-63.
[11] EC. Directive 2009/29/EC of the European Parliament and of the Council amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community. Brussels: European Commission; 2009.
[12] IEA. Policies to incentivise CCS in industrial applications. In CCS 2014: What lies in store for CCS? Paris: OECD/IEA; 2014.
[13] De Bruyn, S., A. Markowska, F. de Jong and M. Bles. Does the energy intensive industry obtain windfall profits through the EU ETS? An econometric analysis for products from the refineries, iron and steel and chemical sectors. CE Delft: Delft; 2010.
[14] DCE. Iron & Steel Capacity Expands amid Elimination. Dalian Commodity Exchange, Aug 06 2013, Dalian. http://www.dce.com.cn/portal/info?cid=1261730309137&iid=1375780961100&type=cms.news. 2013
[15] EC. Ensuring a future for steel in Europe. Memo/13/523 11/07/2013. Brussels: European Commission; 2013.
[16] IEA. A Policy Strategy for Carbon Capture and Storage. Paris: IEA/OECD; 2012.
[17] ERM. Financial Support Mechanisms for CO_2 capture and storage CO_2 Capture Project www.co2captureproject.org. 2009.
[18] GCCSI. The Global Status of CCS: 2010. Canberra: Global CCS Institute; 2011.
[19] Bennett, S. J., M. Kelleher, E. Kruizinga, S. Thon and O. Røsnes. The European CCS Demonstration Project Network - A forum for first movers. *Energy Procedia* 2011, 4:5557-64.
[20] EC. Proposal for a Directive of the European Parliament and of the Council amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources. COM(2012) 595 final. Brussels: European Commission; 2012
[21] EnWG. Gesetzüber die Elektrizitäts - und Gasversorgung (Energiewirtschaftsgesetz - EnWG). German Energy Act, Article 3.10c. Berlin: Bundesministerium der Justizherausgegeben und erscheint; 2005.
[22] Baron, R., I. Barnsley and J. Ellis, Options for integrating sectoral approaches into the UNFCCC. Paris: OECD/IEA; 2008.
[23] Bradley, R., K.A. Baumert, B. Childs, T. Herzog and J. Pershing. Slicing the pie: sector-based approaches to international climate agreements – issues and options. Washington D.C.:World Resources Institute; 2007.
[24] Baron, R., J. Reinaud, M. Genasci and C. Philibert. Sectoral approaches to greenhouse gas mitigation exploring issues for heavy industry. IEA information paper. Paris: OECD/IEA; 2007.
[25] World Coal Association, "Case study: Coal21 partnership". London: World Coal Association; 2011.
[26] EC. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Future of Carbon Capture and Storage in Europe.COM (2013) 180 final. Brussels: European Commission; 2013.
[27] IEA. World Energy Outlook Special Report 2013: Redrawing the Energy Climate Map. Paris: OECD/IEA; 2013.
[28] Climate Strategies. Carbon Control and Competitiveness Post 2020: The Cement Report. London: Climate Strategies; 2014.
[29] EC . Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC. Brussels: European Commission; 2009.
[30] Kongsjorden, H., O. Kårstad and T. A. Torp. Saline aquifer storage of carbon dioxide in the Sleipner project. *Waste Management* 1998, 17:303-8.
[31] Abadie, L.M. and J.M. Chamorro. European CO_2 prices and carbon capture investments. *Energy Economics,* 36:2992-3015.

[32] Demailly, D. and P. Quirion. CO_2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: grandfathering versus output-based allocation. *Climate Policy*, 6:93-113.
[33] Cosbey, A., S. Droege, C. Fischer, J. Reinaud, J. Stephenson, L. Weischer and P. Wooders. A Guide for the Concerned: Guidance on the elaboration and implementation of border carbon adjustment. Policy Report 03. Stockholm: Entwined; 2012.
[34] Helm, D., C. Hepburn and G. Ruta. Trade, climate change, and the political game theory of border carbon adjustments. *Oxford Review of Economic Policy*, 28:368-94.
[35] Cosbey, A. Border Carbon Adjustment. Paper prepared for Trade and Climate Change Seminar, June 2008, Copenhagen Denmark. Winnipeg: International Institute for Sustainable Development; 2008.
[36] Climate Strategies. Carbon Control and Competitiveness Post 2020: The Cement Report. London: Climate Strategies; 2014.
[37] EC. Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006. Brussels: European Commission; 2009.
[38] Alberta Energy. Carbon Capture & Storage.Summary report of the regulatory framework assessment. Edmonton: Alberta Energy; 2013.